

The Implications of Direct Red-Shift Measurement of γ -ray Bursts.

Ehud Cohen and Tsvi Piran

Racah Institute of Physics, The Hebrew University, Jerusalem, Israel 91904

Received _____; accepted _____

ABSTRACT

The recent discoveries of X-ray and optical counterparts for GRBs, and a possible discovery of a host galaxy, implies that a direct measurement of the red-shift of some GRBs host galaxies is eminent. We discuss the implications of such measurements. They could enable us to determine the GRBs luminosity distribution, the variation of the rate of GRBs with cosmic time, and even, under favorable circumstances, to estimate Ω . Using GRB970508 alone, and assuming standard candles, we constrain the intrinsic GRB evolution to $\rho(z) = (1 + z)^{-0.5 \pm 0.7}$.

1. Introduction

The recent observations of the Italian-Dutch Beppo/SAX satellite of γ -ray bursts, (Costa *et al.* 1997), with error boxes of a few arc-minutes across, enabled a follow-up by optical and radio observations and the discovery of x-ray, optical and radio counterparts to GRBs. The optical observations provided, for the first time, independent estimates of the distances to GRB sources, using absorption lines or association with host galaxies, (Metzger, *et al.* 1997), and demonstrated beyond doubt the cosmological origin of GRBs. It is highly possible that in the months to come several GRBs would have independent red-shifts estimates. We may use these to obtain estimates of the luminosity diversity and the intrinsic evolution of the GRB rate with cosmic time. Under favorable conditions we might even be able to use GRBs as cosmic probes for estimating the cosmological parameters.

Given a group of GRBs with measured fluxes and red-shifts we should first calculate the luminosity distribution of the sources . Then using this luminosity function we should estimate the theoretical peak-flux distribution in cosmological models. Comparison of this distribution with the observed one would yield a direct estimate of the cosmic evolution of GRBs - that is the variability of the GRB rate per unit comoving volume per unit comoving time. Depending on the width of the luminosity function, the null assumption of no cosmic evolution could be proven or ruled out with a few dozen bursts. Cosmological parameters like the closure parameter, Ω , and the cosmological constant, Λ , influence only weakly the peak-flux distribution (Cohen & Piran 1995) hence this analysis can be done safely assuming $\Omega = 1$ and $\Lambda = 0$. However, if the luminosity function is narrow enough we might use the peak-flux red-shift relation to obtain a direct measure of Ω .

2. The Luminosity Function.

The association of a host galaxy with a GRB provides us with the red-shift of the host, which is the bursts' red-shift assuming that the burst is close to the host. Additionally we have the usual peak photon flux parameter, $p(ph/cm^2/sec)$, which is transferred later to apparent luminosity, $l(erg/cm^2/sec)$, using bursts' spectra. The peak photon flux vs. red-shift and source luminosity is:

$$p = \frac{N[\nu_1(1+z) \dots \nu_2(1+z)]}{4\pi(1+z)(2c/H_0)^2(1 - \frac{1}{\sqrt{1+z}})^2}, \quad (1)$$

where $\nu_1 = 50\text{keV}$, $\nu_2 = 300\text{keV}$ are the detector boundaries, z is the burst red-shift, c/H_0 is Hubble distance, and $N[\nu_1, \nu_2]$ is the number of photons emitted in the range $[\nu_1, \nu_2]$. We have used $\Omega = 1$ and $\Lambda = 0$ in eq. 1. The effect of Ω and Λ on the luminosity is not large, and we will discuss it later. The luminosity dependence on Hubble constant is a scale factor of $h_{75}^2 = (H_0/(75\frac{Km/sec}{Mpc}))^2$.

When comparing bursts from different red-shifts one must recall that the observed peak-flux is in the range 50 – 300keV. This corresponds to different energy ranges at the sources. In order to discuss a single luminosity that classifies the burst, we will consider $L \equiv \int_{50\text{keV}}^{300\text{keV}} L_\nu \nu d\nu$ at the source. To convert from the observed peak flux to the intrinsic luminosity we assume that the source spectral form is a power-law $L_\nu = L(\nu/50\text{keV})^{-\alpha}(2-\alpha)/(6^{2-\alpha}-1)/(50\text{keV})^2$ in the energy range $50\text{keV} < \nu < 300\text{keV}(1+z_{\max})$, so that wherever the source is, the detector sees a power-law spectra. We will use $\alpha = 1.5$ for all bursts. This value is probably a good typical estimate (Band, *et al.* 1993), even though the spectra is not the same for all bursts . If necessary, one can use the measured spectrum of each burst to estimate its intrinsic luminosity at the 50 – 300keV band, however at this stage this simple estimate is sufficient.

Alternatively one can view the variability in the spectral index as an additional random variable that simply widens the luminosity function. Using this spectral shape we obtain:

$$l = \frac{L(1+z)^{-\alpha}}{4\pi(2c/H_0)^2(1 - \frac{1}{\sqrt{1+z}})^2} = \frac{L(1+z)^{-\alpha}h_{75}^2}{7.7 * 10^{57}(1 - \frac{1}{\sqrt{1+z}})^2} \quad (2)$$

We would be able to obtain a direct estimate of the GRB luminosity function in the observed band when as few as a dozen bursts will be observed. Using eq. 2 we find the luminosity for each burst. Using those luminosities we can estimate the luminosity distribution function using maximum-likelihood or any other statistical method. Recall that current data, and in particular the peak-flux statistics of GRBs does not constrain the luminosity distribution of GRBs (Cohen & Piran 1995, Loredo & Wasserman 1995). Clearly, if the sub-group of GRBs with optical counterparts is biased, this distribution estimate will be biased.

3. Cosmological GRB Evolutions

One of the interesting features that might distinguish between different cosmological GRB models is the rate that GRBs occur per unit time per unit comoving volume: $\rho(z)$. These new measurements could yield a direct estimate of this distribution. Once the GRB luminosity distribution is known we can proceed and compare the theoretical peak-flux statistics (using the observed luminosity distribution) with the observed one. This distribution depends strongly on the intrinsic evolution of GRBs, that is on variation of $\rho(z)$. Following (Cohen & Piran 1995) we characterize this dependence as $\rho(z) = (1+z)^{-\beta}$. Comparison of the theoretical and observed distribution would limit β . The cosmological parameters Ω and Λ influence this distribution rather

weakly (Cohen & Piran 1995) and have no substantial effect in estimating β . Recall that prior to the independent knowledge of GRBs luminosity, one could not distinguish between cosmological effects and intrinsic evolution using count statistics.

In fact this comparison can be done even with the current data and assuming a narrow luminosity distribution (standard candles). We can use GRB970508 to constrain the evolution. Using the peak flux = $1.6 * 10^{-7} \text{erg/sec/cm}^2$, (Kouveliotou, *et al.* 1997), the red-shift of the absorption lines $z = 0.835$ (Metzger, *et al.* 1997) which sets a lower limit $z > 0.835$ for the burst, and the absence of prominent Lyman-alpha forest in the spectrum which compose an upper limit $z < 2.1$, we obtain $\beta = -0.1 \pm 1.3$ in 99% confidence level. Assuming that the absorption line of GRB970508 correspond to its own red-shift we estimate $\beta = 0.5 \pm 0.7$ with this confidence level , see fig 1. The simplest hypothesis of no evolution $\beta = 0$ is consistent with the observations. A milder assumption of Gaussian luminosity distribution with $\sigma_L = L_{obs}/2$, instead of standard candles, gives a lower limit $\beta > -0.7$ and no upper limit.

4. Estimates of Cosmological Parameters.

Despite numerous attempts to estimate the cosmological parameters, there are still large uncertainties. One may wonder whether GRBs would provide a meaningful independent estimate of these parameters. Using GRBs count statistics alone, Ω could not be estimated from the current data (Cohen & Piran 1995). However, given a cosmological distribution of sources with measured red-shifts, we can try to estimate the cosmological closure parameter, Ω , in a similar manner to the attempts to estimate Ω from type I supernovae by Perlmutter, *et al.* 1996.

The observed peak-flux depends on Ω as:

$$l = l(L, \Omega) = L \frac{(H_0/c)^2 \Omega^4 (1+z)^{2-\alpha}}{64\pi(z\Omega/2 + (\Omega/2 - 1)(\sqrt{\Omega}z + 1) - 1)^2} \quad (3)$$

Using the known parameters of each burst (peak-flux and red-shift) we obtain for each burst a function $L_i = L_i(\Omega)$. In the previous sections we have assumed $\Omega = 1$ and obtained $L_i(\Omega = 1)$. For standard candles all L_i must be equal. Given two sources we have two functions $L = L_{1,2}(\Omega)$, with two variable and we should be able to determine Ω .

A luminosity distribution will induce an uncertainty in this estimate that can be approximated by:

$$\sigma_\Omega(z) \approx \left. \frac{d\Omega}{dL} \right|_{\Omega=1,z} \sigma_L = 1/4 \frac{(\sqrt{1+z} - 1)\sqrt{1+z}}{z/2 - 3/2\sqrt{1+z} + 3/2 + z/(4\sqrt{1+z})} \frac{\sigma_L}{L} \quad (4)$$

For $z = 1.5$ we obtain $\sigma_\Omega \approx 2\sigma_L/L$. Thus assuming $\sigma_L/L = 1$, we need 100 bursts with a measured z to estimate Ω with an accuracy of $\sigma_\Omega = 0.2$. Such a goal could be achieved within several years. At present it is not known whether the GRB luminosity distribution is narrow enough and satisfies this condition. However, as we have shown at section 2, the width of the luminosity distribution will be known soon.

5. Future Detectors

In view of the promising avenues that these observations have opened it is worthwhile to examine what will be the effect of future more sensitive detectors on these estimates. Cohen and Piran (1995) have estimates that BATSE is sensitive to bursts up to $z_{max} = 2$. A more sensitive detector (by a factor of 10) will detect bursts up to $z = 6.9$. Assuming that $\rho(z)$ is constant up to high value of z we find that the number of observed bursts will increase only by a

factor of 2.1. The results are slightly better if the current z_{max} is smaller. For example a ten fold more sensitive detector will measure 2.6 times more bursts than BATSE if $z_{max}=1.5$ and 3.5 times more bursts if $z_{max} = 1$.

At first sight these results might look discouraging. However, the rate of GRBs at high red-shift is unknown and could be critical in determining the nature of GRBs. At present it is not known if there are bursts which originate from high z . Most models that are based on compact objects cannot produce sources at very early time. On the other hand these model, and in particular the neutron star merger model predict a high rate of GRBs that will follow with a time lag of up to 10^9 years any extended star formation activity. This is approximately the time it will take the stars in a binary system to finish their life cycle, become NS, loose angular momentum through gravitational radiation, and merge. Nuclear abundances measurement indicates that heavy elements that are produced in supernovae began to be produced earlier than heavy elements produced in neutron star mergers. It will be intriguing to see whether GRB rates would follow the trend of supernovae or neutron star mergers.

Furthermore, , one has to recall that the relevant question for our purposes is not how many bursts are observed but how many bursts are observed with measured red-shifts. Currently the rate of detection of bursts with counter-parts is about one per month and from those detected until now only one has a measured red-shift. Here there is an enormous potential for improvements. For example systematic measurements of the red-shift of all bursts observed by BATSE (≈ 300 per year) would yield an independent estimate of Ω , with $\sigma_\Omega = 0.1$, even if the luminosity function is wide, ($\sigma_L/L = 0.9$), within one year.

6. Discussion and Conclusions

As expected, the direct red-shift measure of GRB970508 agrees well with estimates made previously using peak-flux count statistics (Fenimore, *et al.* 1993, Loredo & Wasserman 1995, Cohen & Piran 1995). It is remarkable what could be done with even several additional red-shifts. An estimate of the bursts' luminosity distribution can be obtained even with a few bursts. This luminosity function combined with the observed peak-flux distribution would provide us immediately with an estimate of the cosmological evolution of the rate of GRBs.

It is generally accepted that Fireball is inevitable in any cosmological model. Within this model the observed γ -rays are produced during the conversion of a relativistic energy flow to radiation. However, the source itself that produces the flow remains unseen (Piran 1996). The limits on cosmological evolution could shed light on the GRB mystery, by distinguishing between different cosmological models. For example the expected rate of merging neutron stars depends on the red-shift in a drastically different way than the expected rate of events related to AGNs.

The implications of these red-shift measurements could reach even further. Detection of a significant group of GRBs with red-shifts could enable us to utilize GRBs to study cosmology. Hundred bursts with associated red-shifts will enable us to estimate the cosmological parameter Ω even if the GRB luminosity distribution is relatively wide. This goal is not practical with the current detection rate. However, if the luminosity distribution is narrow, or if a novel detection technique could be found which will yield a significantly higher rate of counter-part detection, we would be able to measure Ω using this method within several years.

7. Acknowledgments

This research was supported by a US-Israel BSF grant and by a NASA grant NAG5-1904.

REFERENCES

- Band, D., *et al.* 1993, ApJ, 413, 281
Cohen, E. & Piran, T. 1995, ApJ, 444, L25
Costa, E., *et al.* 1997, IAU Circ. 6572
Fenimore, E.E., *et al.* 1993, Nature, 366, 40
Kouveliotou, C., *et al.* 1997, IAU Circ. 6660
Loredo, T. J. & Wasserman, I. M. 1995, ApJS, 96, 261
Metzger, *et al.* 1997, IAU Circ. 6655
Perlmutter, S., *et al.* 1996, astro-ph/9608192
Piran, T., 1996, in *Some Unsolved Problems in Astrophysics*, Eds. J. N. Bahcall and J. P. Ostriker, Princeton University Press.

This manuscript was prepared with the AAS L^AT_EX macros v4.0.

Fig. 1.— The likelihood function (levels 31.6%, 10%, 3.16%, 1%, etc. of the maximum) in (β, L) plane for standard candles., $\alpha = 1.5$, $\Omega = 1$, and evolution given by $\rho(z) = (1 + z)^{-\beta}$. Superimposed on this map is the luminosity of GRB970508, with thick line where the likelihood function $> 1\%$. We have used $h_{75} = 1$.

Luminosity [10^{50} erg/sec] @ 50–300Kev

